UCRL- 94678
PREPRINT

SIZE MEASUREMENTS OF HIGH VELOCITY PARTICLE DISTRIBUTIONS

Charles F. McMillan

This paper was prepared for submittal to
17th International Congress on
High Speed Photography and Photonics
Pretoria, South Africa

June 3, 1986

Lawrence Livermore National Laboratory

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Charles F. McMillan

B.A. (Columbia Union College), Ph.D. (Mass. Inst. of Tech.)

Lawrence Livermore National Laboratory,
L-368, P.O. Box 808, Livermore, CA 94550 U.S.A.

We have developed a technique for measuring size distributions of particles in the 1 to 10μm range that are moving at speeds of up to 4mm/μsec transverse to the direction of observation. In order to study high speed ejecta from shocked lead surfaces, we place a metal mask in front of the surface with a slit to regulate the optical thickness of the spray. The angular distribution of light scattered by the particles passing through a laser beam is recorded on an electronic streaking camera to yield a record of particle size distribution as a function of time. In addition, the intensity of the unscattered light is monitored to provide an estimate of the the optical thickness of the spray indicating the range over which the single scattering approximation is valid for our data. Glass plates containing randomly distributed dots of known sizes provide a static calibration for the system. Analysis consists of comparing calculated diffraction patterns with the patterns from experiments. Initial experiments on shocked lead surfaces indicate that there are two dominant size classes having diameters of approximately 1μm and 6μm.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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Abstract

We have developed a technique for measuring size distributions of particles in the 1 to 10μm range that are moving at speeds of up to 4mm/μsec transverse to the direction of observation. We do this by measuring intensity as a function of angle for light scattered from the particles using an electronic streaking camera to record variations in time. Initial experiments studying particles ejected from shocked lead surfaces indicate that there are two dominant size classes having diameters of approximately 1μm and 6μm.

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INTRODUCTION

In an effort to measure the size distribution of particles ejected from shocked metal surfaces, we have developed a measurement tool which depends on the intensity distribution of light scattered by particles to infer their size, as does the standard polar nephelometer, and is capable of estimating time dependant size distributions when the particles are moving at speeds up to 4mm/μsec. It has long been known that the reflection of strong shocks from free surfaces can cause ejection of material from the free surface[1]. Asay[2] has measured the mass distribution of material ejected from shocked aluminum and lead surfaces, and Shaw[3] and Couch[4] have observed the ejecta from lead surfaces photographically. However, none of these studies gave information about the particle sizes.

The intensity distribution of light scattered from small particles is a standard technique for sizing particles in the 1μm to 10μm range. It has been successfully applied in measuring the sizes of particles such as atmospheric aerosols[5] and soil particles from explosions.[6] Our application of the technique is unique because of the short time scales allowed for collecting data, less than 10μsec. Because our tools for analysing this data are still under development, our goal in these preliminary experiments has been to make size measurements that are within a factor of two of the correct values.

At the most elementary level, the scattering of light by small particles can be treated as the diffraction of light around a stop; a small particle produces a wide diffraction pattern while a larger particle produces a narrower pattern. If the diameter of the particles is a few times the wavelength of the light, then the scattered intensity is adequately modeled by diffraction. If, on the other hand, the particle diameter is comparable to the wavelength of the light, then the more complicated Mie scattering theory must be employed to explain the scattering pattern. When there are many randomly distributed particles, the total intensity pattern will be the sum of the individual patterns provided that the probability of multiple scattering is low.

EXPERIMENTAL TECHNIQUE

Figure 1 shows a schematic of our experimental setup. We use a 102mm powder gun 20m long to accelerate a projectile to 2mm/μsec. This drives a 440kBar shock into a lead target which is in an evacuated chamber. Material ejected from the surface by the shock, passes through a slit in the collimator and then into the beam of an Argon-ion laser operating at 514.5nm. The width of the collimator slit regulates the amount of material that reaches the laser beam and hence the optical thickness of the material. It is chosen so that the probability of multiple scattering in the ejecta will be low enough that we can expect to be able to interpret the data.

The collecting lens, lens 1, transforms the scattered light from an intensity vs. angle pattern to an intensity vs. position pattern at its back focus. This lens is placed so that the intersection between the ejecta leaving the collimator and laser beam will be at the focal point of the lens. In this configuration, the half-angle that will be transmitted by the lens is determined by the ratio of the radius of the lens to its focal length; in our case, the half-angle is approximately 10°.

At the back focus of lens 1, there is a beam stop which is 3.15mm wide. Its primary function is to keep the unscattered light from reaching the photocathode of the streaking camera and burning it. It also serves several secondary functions. It holds an optical fiber that transports the unscattered light to a photodiode which measures the intensity of the unscattered light as a function of time, and hence the optical thickness. As long as the intensity of the unscattered light is greater than $1/e$ times the value when there are no particles present, multiple scattering can be neglected[7]. The beam stop also provides the angular calibration in our records. Since both the width and location of the beam stop are known relative to lens 1, the angular region that it blocks is also known. For small angles, the displacement on the streaking camera record is proportional to the angle so the relation between the width of the beam stop on the record and the angle that it blocks provides the proportionality constant.

The relay lens, lens 2, projects the pattern at the focal plane of lens 1 onto the slit of a Thompson CSF model TSN506N electronic streaking camera. The signal is recorded on Kodak Royal-X Pan film. Before developing the film, we place an intensity wedge having the same spectral distribution as the phosphor of the streaking camera on the edge of the film in order to determine the exposure-density relation for each individual piece of film. A computer program uses the information from the wedge on the film to convert the density to exposure.

The scattering system is calibrated by placing a glass plate with randomly distributed dots into the laser beam. We have calibration plates with 1μm and 10μm dots. Figure 2 shows a comparison between the streaking record from a calibration plate and the diffraction pattern for dots that have a 10μm diameter. The amplitude of the theoretical pattern has been adjusted to match that of the experiment. The notch over the central 2° of the experimental record is caused by the beam stop. As can be seen, the agreement in the shape is very good.

EXPERIMENTAL RESULTS

Figure 3 is a record from a shot with an aluminum collimator 1cm from the lead surface having a slit 4mm wide; part *a* shows the scattered intensity as recorded by the streaking camera, and part *b* shows the attenuation signal recorded by the photodiode. The scattered intensity varies in time indicating changes in the scattering particles in the test volume as a function of time. The attenuation signal indicates that for the early part of the scattering record, the single scattering approximation is valid. The dramatic fall in unscattered light shown in fig. *3b* occurs when the ejecta generated by the lead surface hitting the collimator arrives at the laser beam. The dots along the right hand side of the record are fiducials.

Based on the time of flight from the free surface of the lead, the fastest particles we have observed are moving at velocities up to 4mm/μsec transverse to our laser beam. The lower velocity limit is determined by the velocity of the lead surface and is about 2mm/μsec.

Figure 4 is an example of a trace across the scattering record at constant time. We have taken advantage of the observed width of the beam stop on the film to generate the angles shown. The heavy line in Fig. 4 is the calculated diffraction pattern for 6.7μm particles. The intensity of the calculated pattern is arbitrarily scaled to give a good fit to the experimental data. While the fit is not perfect, it is certainly good enough to get a general idea of the size of the particles. From this experiment, we conclude that the observed particles have a diameter between 5 and 10μm.

Figure 5 is comparable to Figure 4, but taken from a later shot where the aluminum collimator was replaced by a steel collimator. In this shot, there appear to be two size components, one at 6μm and the other at 1μm. The calculated shape was determined by first fitting the diffraction pattern for 1μm particles to the wings of the scattering pattern and then adding to that the diffraction pattern for 6μm particles. While the agreement between the calculated and experimental shapes is not perfect, it certainly indicates the presence of at least two size classes and gives us an estimate of the approximate sizes.

This analysis technique is admittedly crude. Fortunately, the shape of the diffraction pattern is quite sensitive to the particle size in this range so as a first attempt at the analysis, it isn't bad. Figure 6 illustrates this point. It compares three diffraction patterns for particles having diameters from 5 to 9μm in 2μm steps. The amplitudes are scaled so that they are the same at 1°; this is a good mock for our analytical procedure. The differences in the diffraction patterns for these particle sizes are obvious.

We only measure the intensity of the scattered light out to 10°, as a result, our ability to resolve particles smaller than 1μm is limited because all particles smaller than 1μm will present a relatively flat scattering profile over a 10° region. However, the limited angular range simplifies the analysis since the scattering pattern predicted by Mie theory differs little from diffraction for particles down to 0.5μm in this angular range as is shown by Figure 7.

In the future, we anticipate using a more refined technique for inferring size distributions from scattering amplitudes. This inversion problem does not have a unique solution, but techniques such as those outlined by Santer[8], hold the promise of reasonable solutions to the particle size distribution problem.

SUMMARY

We have demonstrated a technique employing light scattering that can be used to estimate the sizes of particles moving at speeds up to 4mm/μsec. Using this technique, we have observed particles in the 1μm and 6μm range ejected from shocked lead surfaces. We wish to express appreciation to Roger Minich for suggesting scattering as a technique for measuring ejecta size distributions, to Richard Whipkey for his assistance in developing the experimental apparatus and in executing the experiments and to William Herrmann for preparing the calibration plates.

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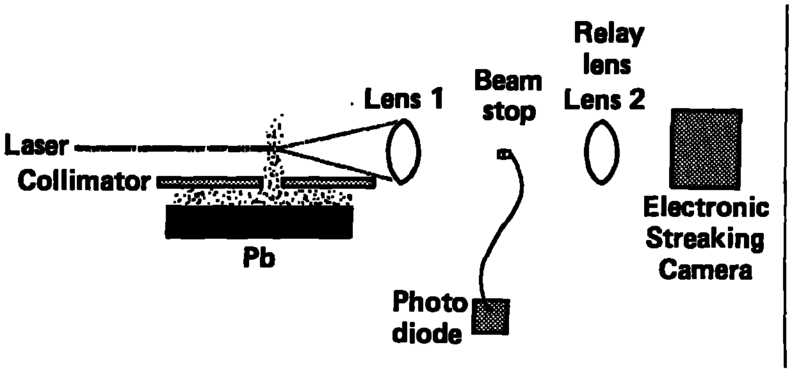

Figure 1. Experimental setup for measuring particle sizes of ejecta.

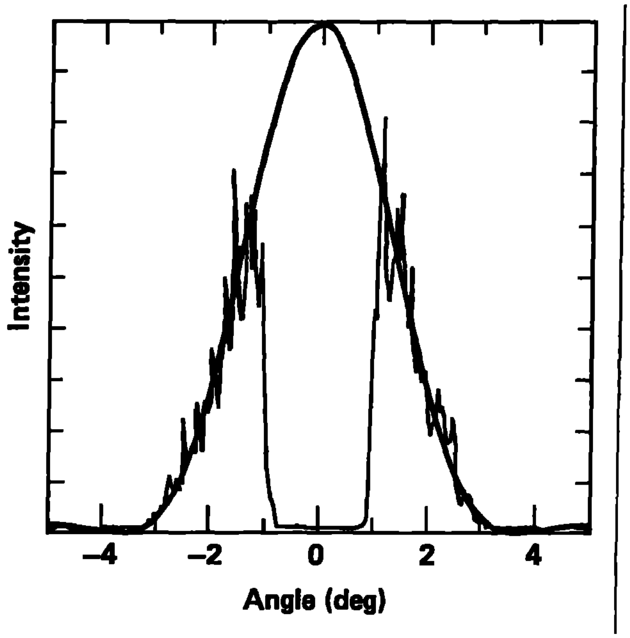

Figure 2. Comparison of scattering from 10μm dots on a calibration plate with calculated diffraction pattern for these dots.

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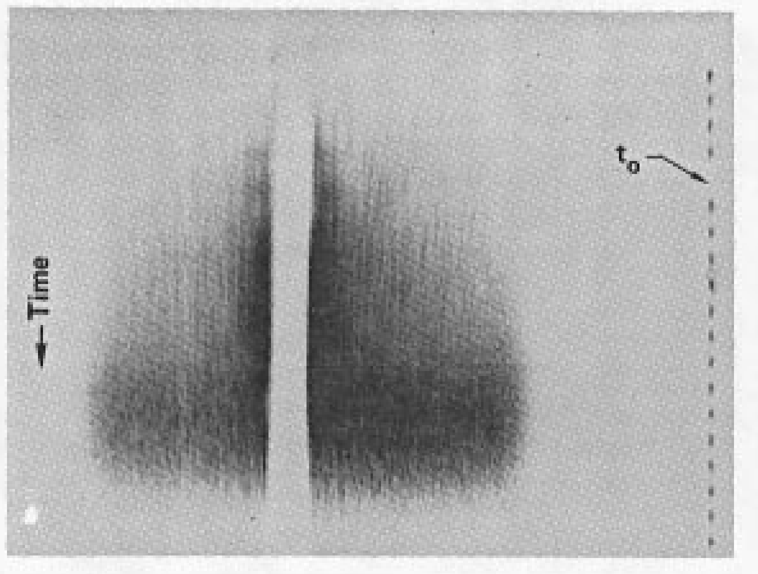

Figure 3a. Scattering signal from lead ejecta.

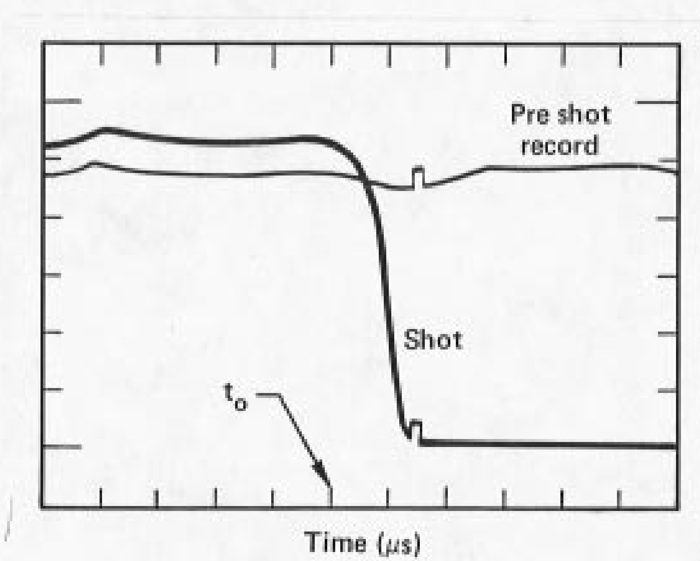

Figure 3b. Attenuation signal from lead ejecta.

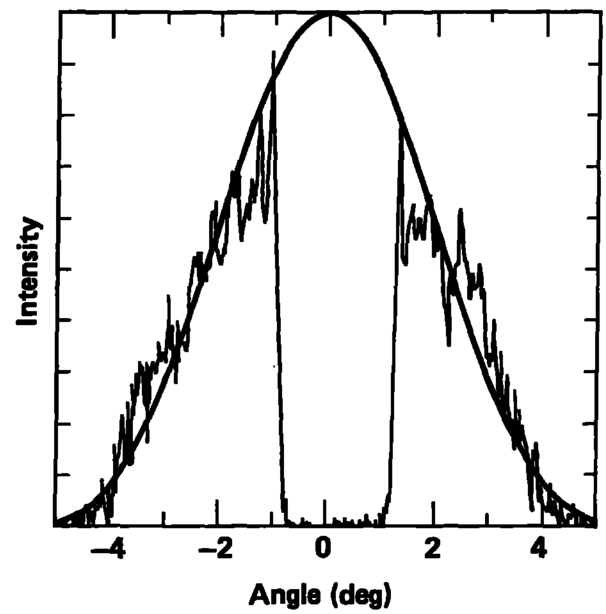

Figure 4. Comparison of calculated diffraction pattern from 6.7μm particles–heavy line, with experimental scattering from ejected lead particles–light line.

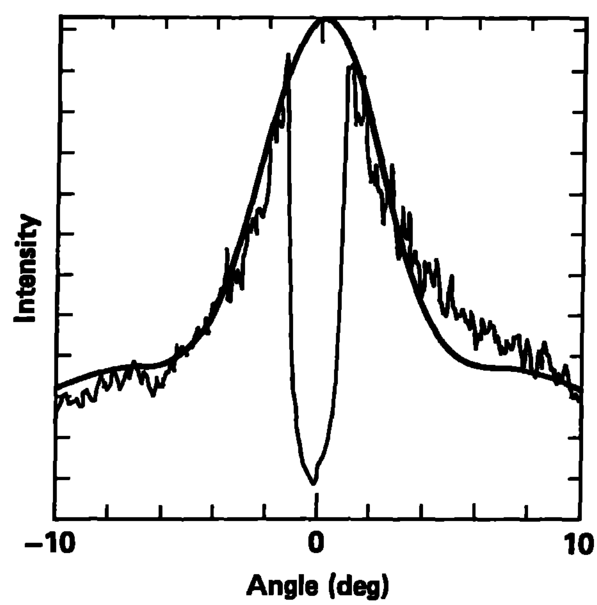

Figure 5. Comparison of calculated diffraction pattern for 1μm and 6μm particles–heavy line, with experimental scattering from ejected lead particles–light line.

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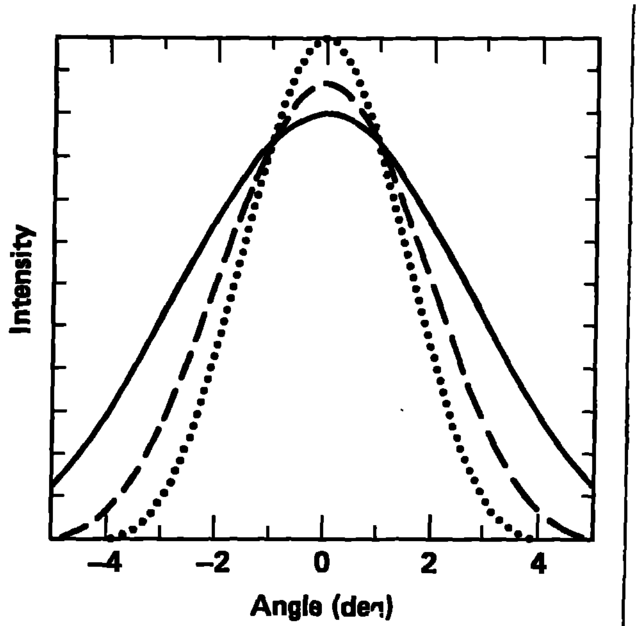

Figure 6. Comparison of calculated diffraction patterns for particles with diameters of $5\mu m$–solid line, $7\mu m$–dashed line, and $9\mu m$–dotted line. The amplitudes are chosen so that they are the same at 1°.

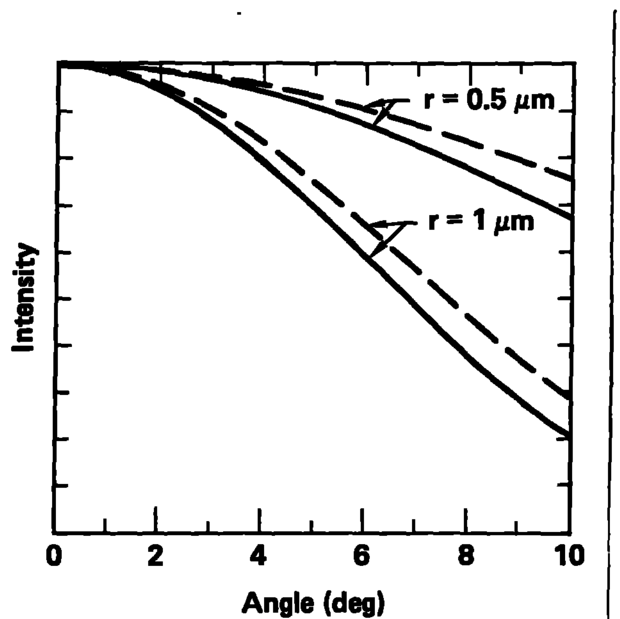

Figure 7. Comparison of Mie scattering–solid line, with diffraction pattern–dotted line, for $1\mu m$ and $0.5\mu m$ particles.

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